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COMMITTEE ON THE PEACEFUL
USES OF OUTER SPACE

NATIONAL RESEARCH ON SPACE DEBRIS

SAFETY OF NUCLEAR-POWERED SATELLITES

PROBLEMS OF COLLISIONS OF NUCLEAR POWER SOURCES WITH SPACE DEBRIS

Note by the Secretariat

Addendum

The present document contains information provided in replies received from Member States up to 21 February 1994.

CONTENTS

Page

REPLIES RECEIVED FROM MEMBER STATES*

United Kingdom of Great Britain and Northern Ireland 2

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V.94-21084T

UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND

[Original: English]

In April 1993 the British National Space Centre co-sponsored the First European Conference on Space Debris held in Darmstadt, Germany and hosted by the European Space Agency. This meeting was established as a major international forum for the discussion of technical and legislative problems associated with orbital debris.

The first UK Orbital Debris Industry/Academia Coordination Group Meeting was held in London on 2 September 1993. Representatives from UK Government, Industry and Universities met to coordinate a national initiative aimed at combatting the orbital debris problem. A round table discussion concluded that both short and long term risk analyses should be carried out to identify and characterise the dominant hazards to current and future space assets.

A number of technical papers have been produced by UK researchers during 1993:

The problem of predicting the long term growth of the satellite and debris population in Low Earth Orbit (LEO) was explored by McInnes[1]. The work was extended to consider the possibility of self-sustaining cascade fragmentations and identified the dominant influence of orbital altitude, and therefore atmospheric density and drag on the rate of buildup[2].

UNISPACE, the Unit for Space Sciences at the University of Kent, continue to enhance their retrieved surface analysis capability and add to the growing database of impact phenomena. The Unit continues to lead the debate on the relative contribution of debris and meteoroids to the LEO particulate environment[3]. This analysis is enhanced by studies of crater morphology to permit deconvolution of flux characteristics and therefore population statistics[4]. This effort aimed at analysis of retrieved surface analysis from satellites such as the Long Duration Exposure Facility (LDEF)[5], is also supported by hydrocode modelling[6]. UNISPACE studies indicate the presence of a population of debris in eccentric orbits which is not represented by the current engineering models, but which can have a profound impact on satellite and shielding design.[7]

The Defence Research Agency carried out investigations into the reentry prediction of risk objects[8] and used the PION reentry prediction campaign, coordinated by the European Space Agency, to improve understanding of the reentry processes. The Defence Research Agency also carried out simulations of the effect of satellite breakups within LEO constellations[9] and sought design measures to minimise both the vulnerability of both the system to such an event, and also the general population of LEO satellites. The Defence Research Agency also carried out a programme of research with the Royal Greenwich Observatory and the University of St. Andrews to consider the selection effects associated with optical sensing of objects on the geostationary ring[10]. It was concluded that the threshold minimise size of object that can be detected by optical systems is influenced greatly by the departure from the nominal geostationary values of the object's orbital eccentricity and inclination. Consequently debris objects, whose trajectories would be allowed to drift from the nominal geostationary values would only be detectable at larger size regime. This may explain why only a small population of debris has been detected at geostationary altitudes to date.

This optical sensing effort was complemented by the Royal Greenwich Observatory and University College, London[11] who sought novel optical detecting systems to improve threshold minimum detectable sizes and relieve operational constraints. Further work considering the detectability of a breakup event in Geostationary orbit is in preparation.[12] The Defence Research Agency also considered the buildup of debris in LEO, highlighting the increased hazard to polar orbiting platforms, and concluded that the collision risk will continue to grow at altitudes above 500-600 km.[13]

In association with the Defence Research Agency, the University of Southampton[14] is developing theory and tools to model the short term effects of satellite breakups on operational vehicles and on the general population.

AEA Technology continue to develop their hypervelocity impact simulation capabilities. In addition to light gas gun technology, electromagnetic railgun technology has been investigated[15] to simulate impacts at orbital velocities.

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CONTENTS

Page

REPLIES RECEIVED FROM MEMBER STATES*

Germany 2

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GERMANY

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Since space debris is a problem of high and rising concern to all spacefaring nations as already pointed out in UN Doc. A/AC.105/420 of 15 December 1988 (Environmental Effects of Space Activities), Germany expressly welcomes the decision to institutionalize "Space Debris" as a separate agenda item in the Scientific and Technical Subcommittee of UNCOPUOS. For years, the German delegation in UNCOPUOS has helped during the NPS debate to prepare this important step which should ultimately lead to proposals of UNCOPUOS to deal effectively with the problem of space debris on an international basis.

In order to reach this goal, Germany is eager to contribute to the deliberations under the agenda item "Space Debris" in the Scientific and Technical Subcommittee. Germany has submitted annual reports on national research activities in the field of space debris to the Scientific and Technical Subcommittee of UNCOPUOS. The last report is contained in document A/AC.105/542/Add.2 of 14 February 1993. The present paper reports on the work done since then.

German activities in the field of space debris cover a wide range. An assessment of all these national activities was made during a workshop organized by the German Space Agency DARA on 9 December 1992 [1]. On 2 December 1993, DARA arranged another workshop on "Impediments for space activities through space debris - Research activities, threats, and possible solutions". 30 experts participated in this workshop and discussed 10 papers which were presented by German as well as ESA and UN representatives.

The wealth of German research activities can be grouped under the following headings:

- methods of debris detection;
- modelling of space debris;
- trend analysis;
- investigation of hypervelocity impact phenomena;
- test and numerical simulation;
- development of debris protection systems;
- debris prevention and removal.

German research activities can be distinguished in that they are either conducted on a purely national footing or they are funded under contracts with the European Space Research and Technology Center (ESTEC) and the European Space Operations Center (ESOC) of the European Space Agency (ESA).

As a major event in international cooperation in space debris research, the First European Conference on Space Debris took place in Darmstadt (Germany) from 5 to 7 April 1993. DARA was a co-sponsor for this meeting which brought together 250 experts from 17 countries [2] including a large German delegation.

The nationally funded research activities are largely concentrated in the Institute for Space Flight Technology and Nuclear Reactor Technology of the Technical University of Braunschweig (IfRR/TUBS) and the Research Establishment for Applied Science (FGAN) under research contracts awarded by DARA and ESA.

Based on the ongoing space debris modelling activities and model validation by interpretation of measurements [4], [6], [8], [10], [11], [13] the work at IfRR/TUBS has been extended to the detailed analysis of future scenarios and debris mitigation measures [3], [5], [11], [13], [15]. Most of the work has been performed in close and successful cooperation with researchers at the United States National Aeronautics and Space Administration (NASA). The work at IfRR/TUBS is funded not only nationally but also by the

European Space Agency (ESA). This reflects the experience of IfRR/TUBS and its standing on matters of the European space debris research.

Space debris related studies at FGAN are aiming primarily at the development and improvement of radar techniques to detect, classify and identify targets [16], [17], [18]. The existing Tracking and Imaging Radar (TIRA) is also employed for space debris observations:

- In 1990 DARA signed a study contract with FGAN for the investigation of physical characteristics of selected space debris through analyses of narrowband and high resolution radar data. Currently a list of 30 space debris objects (larger than 0.50 m) is agreed with NASA, Houston. NASA scientists are performing optical measurements. Exchange and comparison of radar and optical analysis results are part of the work [19]. The contract will last until June 1995.

- In February 1993 ESA/ESOC signed a study contract with FGAN to investigate radar detection of mid-size space debris (size regime 1-50 cm). Concepts will be suggested for modifying the signal processing of the FGAN tracking radar to track mid-size space debris. Measurements of the debris population in specified orbit altitude regions will be conducted to prove the feasibility of concepts [20]. The contract will last until April 1994.

Additional ESA-funded activities concentrate on meteorid/debris-protection systems, especially in the framework of the Columbus programme. Also covered are investigations of hypervelocity impact phenomena by tests (Ernst Mach Institute) especially the phenomena of impacts on pressurized vessels and the improvement of test facilities (Battelle Institute) in order to reach higher velocities, as well as tests with representative tanks at this institute.

Further activities are funded by the German aerospace industry in the field of protection systems, using its own resources.

The following describes the work in more detail.

I. Space debris modelling

Assessing the present and future risk to all space objects by the Space Debris Environment requires the use of models. The ESA MASTER Model (Meteorid And Space Debris Terrestrial Reference Model) [10] has been developed by IfRR under an ESOC contract. The scope of the model covers man-made and natural objects larger than 0.1 mm in altitudes below 2000 km. Analytical break-up models are used for the individual generation of the untrackable debris population for the known on-orbit fragmentations (116 up to 07/93). The observable part of the population is considered by the implementation of ground based radar measurements. For each generated population member, information is retained on its origin, mass, size and orbit. The population can be propagated to a reference epoch, at which a 3D (radius, right ascension, declination) spatial density distribution and the resulting flux to any circular or elliptic user defined target mission can be established. Flux information is resolved with respect to the impactor source, its mass, the impact velocity, impact azimuth angle, impact elevation angle and the position of the impact occurrence along the target's orbit.

The historical orbital fragmentations have been simulated at IfRR/TUBS and the corresponding object flux has been established. The flux resulting from these simulations is smaller than that observed by deterministic sources e.g. space returned hardware (LDEF) and is adapted to the measurements for application purposes. Currently ongoing studies will extend the model up to the GEO region and will provide a CPU time efficient, user friendly and highly accurate analyst and engineering application to be distributed via CD ROM. The model will be applicable on both Work Station and PC environments and will include several features

for spacecraft designers and operators as well as for ground based observatory operators. It will enable a broad user community to carry out investigations on space debris, which have previously been reserved to debris analysts with powerful computer hardware.

II. Validation of small particle model with LDEF data

The work on this item (cf. Doc. A/AC.105/542/Add.2) has been continued [6], [11], [12]. The analyses carried out underline the existence of a large number of small debris particles orbiting on highly elliptical orbits with low inclinations. In addition, the existence of small particles on sun-synchronous orbits (near-circular with high inclinations) must also be assumed to explain the observational data on LDEF's leading surface. If the observed increased flux on the trailing edge of LDEF is real, the basic assumption in the current debris models, namely the ascending nodes of debris particles to be randomly distributed, have to be changed. Only by assuming particle streams with nodes close to LDEF's node, can more crater numbers on the trailing surface than on adjacent surfaces be explained.

From further analyses, which allow for the conversion of crater frequencies into particle fluxes, it can be assumed that present orbital debris models are underestimating the environment in the 0.1 mm size range by a factor of 2 to 3. Hence, the impact data to be gained by the retrieved EURECA platform and the HUBBLE space telescope solar array will be of major importance in view of this topic.

III. Future increase of orbital debris and prevention of additional debris generation

It is in the interest of all spacefaring nations to prevent additional debris generation. A steady increase of the population within a limited space, as low earth orbit (LEO) is representing, will finally lead to collisional cascading effects.

Despite all uncertainties of debris modelling in general and long term simulation in particular, the basic tendencies of the results of the analyses carried out are reliable because the process of interactive collisions is absolutely dominated by the population of large, trackable objects (payloads and rocket bodies), for which deterministic data is available. This is why debris prevention measured in this frame should be concentrated on the avoidance of large objects. At IfRR computer simulations have been carried out in order to evaluate the population in LEO over 50 years considering also fragments generated by collisions. For this purpose a number of realistic scenarios have been taken into account:

1	1992 current population level, only for the means of comparison
2	'business as usual', i.e. continuation of current spaceflight activities
3	easily achievable mitigation measures (reduction of explosion rate and mission related objects to half from 1998)
3a	in addition: total avoidance of rocket body (R/B) explosions from 1998
3b	in addition: total avoidance of payload (P/L) explosions from 1998
3c	in addition: de-orbiting of R/B from 2003 after mission
3d	in addition: de-orbiting of P/L from 2010 after mission

Table 1 List of simulated debris prevention scenarios

Figure 1 gives, as an example, the number of objects > 1 cm in LEO up to the year 2042 can be obtained as a result of the a.m. simulations. These compulations show, that both, explosion prevention and de-orbiting of large objects are necessary to reduce the collision rates. But even assuming the implementation of all preventive mitigation measures (scenario 3d of Tab. 1), there would be a smaller, but steady increase in the population.

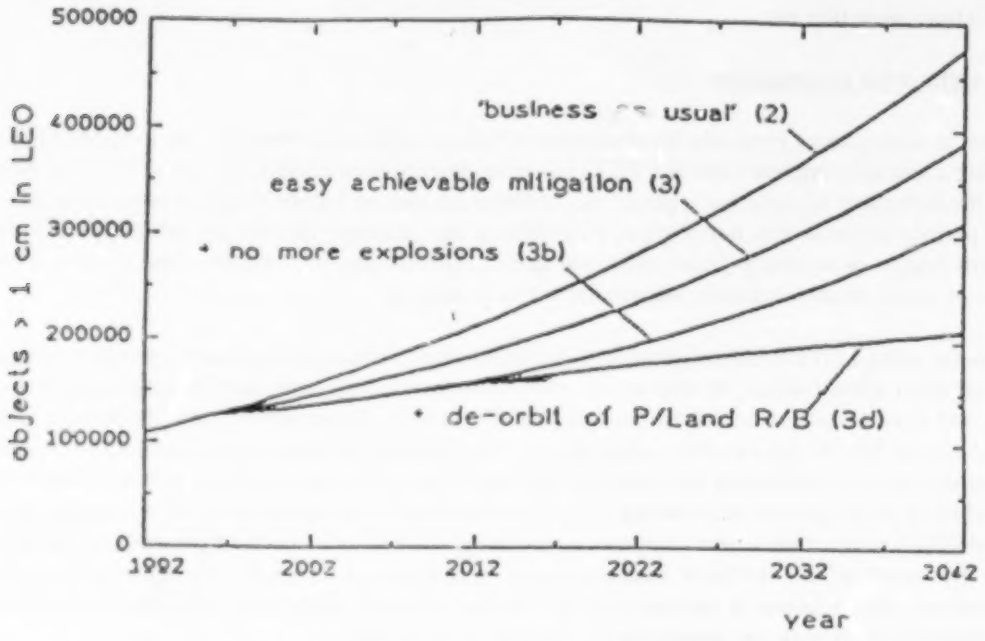

Fig.1 Evaluation of the number of objects > 1 cm in LEO assuming different debris prevention measures

This indicates that the critical population which leads to collisional cascading effects may already have been reached.

While discussing the necessity and the effectiveness of debris mitigation measures, their technical feasibility and their costs must be taken into account as well. Basically, it can be stated that all mitigation measures simulated according to Tab. 1 are feasible, however, they would cause quite different additional costs [6], [12]:

scenario 3:	should be obtainable at very low cost
scenario 3a:	passivation of rocket bodies by venting of residual propellant requires initial moderate cost for the generic rocket type modifications, but no recurring costs.
scenario 3b:	prevention of payload explosions is more sophisticated. Intentional explosions can be avoided free of cost, the avoidance of battery explosions might be achievable at low cost.
scenario 3c: and 3 d:	de-orbiting of orbital objects is always accompanied by the expenditure of propellant. For the de-orbit thrust device, a mass penalty, i.e. increased launch cost of about 5 %, has to be assessed for rocket bodies and 10 % for both payloads and rocket bodies, assuming reentry from a circular orbit of about 1000 km altitude. For 2000 km altitude the mass penalty would be nearly twice as high. The de-orbiting of objects from still higher circular orbits seems economically unfeasible, the same as from geosynchronous orbit.

For such high orbits post-operational re-orbiting to altitudes less used for spaceflight seems to be appropriate.

The conclusion therefore is that besides the avoidance of mission related objects and of explosions in orbit in the short term, also the de-orbiting of rocket bodies and payloads after completion of their mission should be discussed with a view to prevent the uncontrolled increase of the debris population. The work of IfRR/TUBS on this subject will be continued since there are various special aspects, e.g. de-orbiting from GTO, using lifetime reduction etc.

IV. Long term orbit propagation

In order to assess more precisely the long term effects of orbit mechanics for the purpose of space debris modelling a special computer code (LOPEX) has been developed at IfRR/TUBS [4]. This code allows for analyzing the behaviour of different types of orbits (from circular to highly elliptical in various altitude regimes) over periods up to several hundreds of years taking into account the relevant orbital perturbations with a sufficient degree of accuracy. Since this code makes efficient use of computer time it can not only treat the orbits of single objects but also analyze clouds of fragments.

Simulation using LOPEX indicate that the long term effects occurring especially on highly elliptical orbits due to lunisolar perturbations, in interaction with atmospheric drag and solar radiation pressure, are very complex and have to be considered in the space debris models. These effects can be used for debris prevention (cf. section III) to significantly reduce the orbital lifetimes of spent rocket bodies and payloads by means of natural forces. Considering those altitude regimes, where man-made objects will accumulate (i.e. high circular orbits up to the geosynchronous region), simulations show the dynamics of the orbital precession even over hundreds of years. Hence, this computer code can be used to evaluate the effectiveness of storage concepts (e.g. graveyard orbits) for those kinds of orbits, which will not become subject to direct debris prevention measures due to technical and economical reasons. Also the interaction of debris on GTO and other highly elliptical orbits with the geostationary ring can be analyzed.

For the ongoing space debris related work at IfRR/TUBS LOPEX will be used as long term orbit propagator tool for those applications which require a detailed analysis from the orbit mechanics point of view.

V. Active removal of large space debris with the help of a space tether

The accumulation of debris objects on near earth orbits threatens current and future space flight activities. Hence measures are necessary to avoid and remove space debris. As investigated in detail in [5] and described in document A/AC.105/542/Add.2 and A/AC.105/510/Add.2, the large objects, especially spent payloads and rocket upper stages, are of decisive importance for the future evolution of the population in orbit. If their number is not decreased, a chain reaction of collisions will set in. If preventive measures are not sufficient [5] or are not implemented sufficiently early, then active removal of several thousands of large objects from 700 to 2000 km altitude becomes necessary. This cannot be achieved by common methods, e.g. by the use of an orbital manoeuvring vehicle, because of the high propellant demand per removed object.

At the IfRR/TUBS therefore, a principally new, exonomic removal strategy has been developed and investigated [3], [8]. The main element of this strategy is a (conductive) space tether with a diameter of 2 - 3 mm and a length of 150 - 300 km which can be deployed from a special remover vehicle. After a rendezvous and docking manoeuvre with the selected target object, this object is roped down towards the earth. After some adjustments of the orbital elements of the tether configuration [3], the space debris object is separated from the tether at the right time and at the right place and re-enters. The cycle can start again with the rendezvous manoeuvre with the next debris object.

The basics and manoeuvre sequences of this strategy are explained in more detail in document A/AC.105/542/Add.2 and A/AC.105/510/Add.2.

To improve the efficiency and to decrease the threat to the tether posed by small debris particles, the shortening of the tether has been investigated. According to [14] the resistance of the tether against particle impacts can be decisively increased by the use of three-dimensionally woven Kevlar fibres. For the shortening of the necessary tether length without any additional costs the deflection of the tether during roping down and the subsequent tether swing can be utilized [3]. A shortening of the tether length means a reduction of the tether weight and a reduction of the collision risk for the tether.

VI. Shielding and impact analysis

In the past, spacecraft were not designed to withstand debris impacts. But for future space systems, especially manned systems, protective measures are absolutely necessary.

The German industry is involved in the development of effective shielding of manned modules against debris impacts. For pressurized modules it is essential that they do not burst following a meteoroid/debris (M/D) impact according to the environment derived from certain probability requirements, as defined in the system requirement document. The meteoroid and debris protection requirements are some of the driving forces of the design.

As one of the problematic areas, it can be stated that a burst of a pressurized module is by far the most severe failure mode. Further impact tests with pressurized structures have been performed. For analysis and interpretation of the results, adequate structure/fracture mechanics methods and tools are not yet available, but they are required to allow the assessment and the definition of critical damage sizes.

Any burst caused by an M/D impact must be prevented by an adequate design, subject to rigorous control within the fracture control programme. DASA/ERNO is negotiating with ESA to investigate the conditions of burst under M/D impact.

Another ESA/ESTEC study with the Ernst Mach Institute (EMI) as subcontractor to Engineering Systems International (ESI, France) is assessing the capacity of computer codes to describe quantitatively the key parameters of the impact damage. The use of computer codes to simulate hypervelocity impacts is required due to the limitation of test facilities. Impact tests with the light-gas-gun at EMI have been performed for calibration of the mathematical model. This light-gas-gun is one of the most powerful of its kind in the world and is very well suited for the investigation of the hypervelocity impact phenomena.

Further ESA/ESTEC studies with Battelle are in progress, first to assess the feasibility of methods to allow acceleration of 1g projectiles to velocities above 10 km/s by using shaped charge techniques, and second to perform impact tests with representative tank structure, based on Ariane 4 upper stage tank.

The shielding related work at IfRR is based upon the detailed knowledge of the directionality of the small particle flux and the related velocity distribution (cf. section II). The computer codes developed at IfRR for shielding analysis (cf. doc. A/AC.105/542/Add.2) consider also realistic bumper codes and penetration functions. Hence, it is possible to design shielding devices with reduced mass taking into account the a.m. flux directionality and self shielding effects, which depend on the geometry of the spacecraft and its orbit related orientation. This activity emphasizes the necessity of updating the model for small sized debris by the implementation of measured data on surfaces retrieved to earth e.g. LDEF). Only a sophisticated and validated small particle model allows for improved shielding design.

VII. Radar detection and measurements of orbital debris

The FGAN Tracking and Imaging Radar (TIRA) is used to measure radar data of selected debris objects (size larger than 0.50 m). TIRA consists of a narrowband tracking radar and a high resolution imaging radar. Both radars are supported from a 34 m parabolic antenna. Methods and techniques for analyzing narrow-band radar signatures and computing radar images from high resolution radar data of larger objects have been developed. These methods and techniques need further improvement and refinement to cope with mid-size space debris (size 1-50 cm) [16], [17], [18].

VII.1 Physical characteristics of space debris

The objective of a NASA/FGAN joint research investigation is to characterize and compare debris shape, size, intrinsic motion, mass, and orbital lifetime from different types of breakups, for example from collisions and from explosions. At present radar data of a number of 30 debris objects (size larger than 50 cm) are analysed [20]. A statistical analysis of measured radar cross section (RCS) and a comparison with NASA results derived from effective areas of infrared, optical, and radar measurements have been started.

VII.2 Radar detection of mid-size space debris

The objectives of an ESA/ESOC Effort focusses on [20]:

- theoretical and experimental investigation of the detection limits of TIRA in its current version and estimation of the detection probability of space objects,
- investigation of modifications to TIRA to detect and track mid-size space debris (size regime 1-50 cm) in low Earth orbits. This includes analysis and evelopment of concepts for special tracking techniques, signal processing, data handling, and processing algorithms,
- radar experiments using the existing or an upgraded TIRA system to demonstrate the feasibility of suggested concepts.

Data collected during radar experiments will be used to test current space debris environment models.

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